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# An overview of the research and development of Solar flat plate collectors

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***Abstract***
*In an industrial setting, solar flat plate collectors are machines that capture solar thermal energy and use it to heat rooms or water. Flat plate collectors are widely used for low to medium heating applications and are continuously improving in terms of size reduction and efficiency. An overview of the many methods used to improve the effectiveness of flat late collectors is provided in this work. This paper has examined the effects of using Nano fluids as a heat transfer fluid, changing the design of absorber plates to better capture radiation, reducing heat loss, using polymers, using mini channels for fluid flow, using PCM (phase changing materials) to provide heat at night without a tank, and using enhancement devices like inserts and reflectors. Along with the development methodology, a brief overview of the many methods used to analyse the effects and different designs has also been provided. CFD models and a few analytical researches have also been discussed. This review paper also discusses suggestions for further studies to better understand heat transfer from solar flat plate collectors.*

## INTRODUCTION

Along with the development methodology, a brief overview of the many methods used to analyse the effects and different designs has also been provided. The CFD (Computational Fluid Dynamics) model for a solar flat plate collector, as illustrated in Figure 1, is a numerical representation of a real-world thermal collector designed to analyze the heat transfer and fluid flow behaviour inside the system under solar radiation. CFD models and a few analytical researches have also been discussed. Additionally covered in this review paper are recommendations for future research projects aimed at understanding heat transfer from solar flat plate collectors. Heat is transferred from a remote source to a heat-transfer fluid that passes through a solar collector, a sort of heat exchanger [17]. When solar radiation strikes the collector's absorber plate, thermal energy is subsequently transmitted to the fluid. Solar collectors can be divided into two categories based on their design: concentrating and non-concentrating. The Non-concentrating type is further subdivided into evacuated tube collectors and flat plate collectors. The most prevalent and archaic kind of collectors are flat plate collectors. Hottel and Woertz [28] and Hottel and Whiller [29] created the first solar flat plate collectors in 1942 and 1958, respectively. They had created the collectors, which included an insulating shell, a transparent cover, heat transfer fluid, and a black flat plate absorber. Selective black surfaces were used by Tabor [38] in 1955 to increase collector efficiency. His optical concentration experiments demonstrated that high pressure steam could be produced via optical concentration. Since then, numerous researches have been conducted to examine and raise the collector's thermal efficiency.

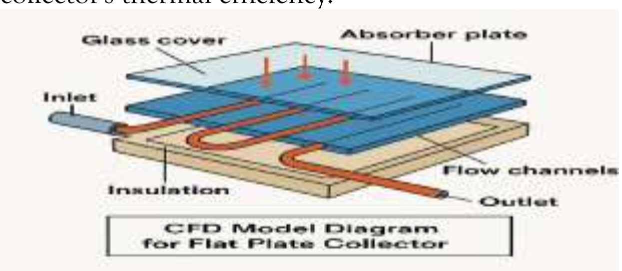


Fig 1.CFD model for Solar Flat plate collector

Solar energy is being considered as a source of endless energy due to the escalating energy issues. In this regard, solar collectors have been extensively researched. After 1990, many of the new designs were developed. Around the world, numerous studies are being conducted to enhance the flat plate collectors' thermal performance. Novel collectors are made of polymers to lighten their weight. By providing the same output as large collectors in comparatively smaller sizes, the use of nanofluid compacts the collectors [32]. With the aid of improved manufacturing and material science procedures, absorber plates have undergone numerous alterations. The optimal spacing between the glass covers in a multi-glazed collector is another area of research. To get the optimal design for the intended working conditions, testing are conducted both indoors and outdoors based on the operational and design requirements. The reduction of heat loss from the collector is crucial for increasing efficiency. Numerous research are focused on reducing heat loss, including those that use honeycomb maze absorber plates, greater glass, collector analysis that takes wind velocity into account, etc.
Evaluating the collector's performance is similarly crucial since it aids in the design's advancement and enhancement. In actuality, analysis and development are inextricably linked. It is not possible to conduct an experimental investigation of every collector that has been produced. As a result, analytical and numerical techniques have been used to roughly analyse the collector's behaviour under various circumstances. Researchers have benefited greatly from CFD codes. Computational Fluid Dynamics (CFD) offers several distinct advantages, including the ability to accelerate development timelines, examine systems under hazardous or extreme conditions, and simulate scenarios that are difficult or unfeasible to replicate physically [39]. Various investigations have explored areas such as the design and optimization of novel absorber plate configurations, the role of nanofluid in enhancing thermal performance, methods to reduce thermal losses to the surroundings, the performance of collectors made from polymeric materials, and the influence of auxiliary components like reflectors and flow-altering inserts.

**2. Techniques and methods for analysis**

Yasin and Hakan [1] carried out a comparative investigation of natural convection phenomena in both flat plate and wavy solar collectors. The study cantered on evaluating the effects of critical parameters, including the Rayleigh number, collector tilt angle, aspect ratio, and surface wavelength, on thermal performance. Commercial CFDRC software was used to simulate laminar flow and thermal fields. A mathematical model was created assuming constant fluid characteristics and ignoring viscous dissipation. Walls that were vertical were regarded as adiabatic. The findings indicated that natural convection and heat transfer were significantly impacted by the col- lector's form and inclination angle. In every instance, the wavy collector's heat transmission was greater than the flat plate collector's. The study revealed that in wavy collectors, the Nusselt number exhibited an oscillatory pattern, whereas in flat plate collectors, it followed a linear trend. Additionally, for a constant aspect ratio, a decrease in wavelength led to an increase in the average Nusselt number. The maximum inclination angle was found to have the highest Rayleigh number, in contrast to a flat plate collector. The applicability and validity of CFD models for assessing solar collectors based on their thermal performance were investigated by Selmi et al. [37]. The CFD model was validated by the authors using a 3-D temperature distribution throughout the entire collector volume. In order to determine the fluid's exit temperature empirically and compare it with the output of the CFD model, an experimental setup was constructed. The analyses were conducted with and without a cover plate, as well as with and without water flow. To make the CFD model analysis more realistic, the flux of solar radiation was changed while maintaining the same values for all other parameters. Despite the experimental flaws, the results of this comparison investigation demonstrated a good agreement between the experimental and CFD results. The findings demonstrated that the thermal performance of flat plate collectors can be reliably assessed using CFD. Grine et al. [34] conducted a study on an air-based solar collector to assess the local and average temperature distributions of the working fluid, the outlet air temperature, wall surface temperatures, heat transfer from the air to the collector walls, and the convective heat transfer coefficient. To overcome the complexities associated with numerical methods, the researchers developed an analytical model aimed at predicting the thermal performance of a flat plate solar collector operating under forced convection conditions. To solve the energy equation for fluid flow within the solar collector, the researchers employed the Green's function method. This analytical approach enabled the calculation of local heat transfer coefficients and allowed for the estimation of two-dimensional air temperature distributions both inside and beyond the collector. The model also facilitated the determination of critical design parameters such as the local Nusselt number, fluid temperature, and wall temperature of the collector. Based on their results, which indicated a decline in the Nusselt number beyond 1.2 meters from the inlet, the authors enhanced their model by incorporating fins beyond this point to boost thermal performance. Experimental results validated the analytical model. Applications for flat plate solar collectors often include space heating, water heating, industrial process heating, etc. Collectors will inevitably operate in dynamic environments in these real-world applications. Dynamic analysis is therefore crucial for accurate thermal performance analysis of such a system. Since dynamic conditions are not taken into account by the steady state model generated from the steady state test (SST), a dynamic model must be constructed. On this subject, numerous researchers have developed a variety of models. Deng et al. constructed one such model [13]. When the instantaneous solar radiation fluctuated dramatically, many of the previous models were less accurate in determining the momentary thermal properties of the output temperature and useful heat gain. To determine the transient thermal characteristics of the collector, the researchers addressed the problem by formulating an analytical model using a series expansion approach, taking into account the concept of effective thermal capacitance. To precisely forecast the instantaneous useful heat gain, the model included a thermal inertia adjustment in addition to steady state useful gain. An air solar collector experiment was conducted, and the model was validated using the data collected. The air solar collector's transient thermal characteristics were properly predicted by the model. As long as they qualify for SST, it might also be used to other collectors. Cerón et al. [2] designed a three-dimensional numerical simulation aimed at assessing the efficiency of flat plate solar collectors. To ensure the reliability of the model, heat transfer data from the riser pipes and the air gap were cross-validated against recognized experimental benchmarks. These included various heat interactions such as absorption, transmission, and reflection of solar radiation; natural convection in the air cavity; heat conduction across the tube-absorber welded junction; mixed convection flow in the risers; and heat losses by convection and radiation to the ambient. The experimental data was used to validate the numerical model's results. The traditional flat-plate solar thermal collector served as the basis for the geometric model, which was reduced to three pipes for numerical analysis while preserving the aspect ratio. For numerical modelling using a three-dimensional governing system of equations based on the RANS turbulence model, a steady-state uniform flow distribution at the tube inlet was taken into consideration. Using the Boussinesq approximation, buoyancy effects were taken into consideration. Free convection flow between the glass cover and absorber plate was taken into consideration using turbulence modelling, and the solar load was addressed using a combination of the Surface to Surface (S2S) radiation model and the Solar Ray Tracing (SRT) method. To minimise grid size, the computational area was split into two subdomains. One study focused on the air gap and its surrounding insulation, while the other considered the assembly of the working fluid tube and absorber, along with the corresponding insulated volumes. The calculations were carried out using the Finite Volume Method (FVM) approach in FLUENT. The SIMPLE algorithm was employed for velocity-pressure coupling, and the second-order UPWIND scheme was used for discretizing the momentum, energy, and turbulent transport equations. In comparing the heat transfer in the tube-side to that of a horizontally oriented pipe with a uniformly heated wall, the results showed that the Nusselt number was higher in the fully developed flow region. When a radiation model was applied, it accurately simulated the absorption and transmission of solar radiation. The average Nusselt number observed inside the air cavity aligned well with experimental correlations, displaying a comparable trend. Overall, the experimental and numerical results demonstrated a good trend for the heat loss coefficient, exact agreement in the optical factor, and good agreement in the behaviour of the solar collector. In their study, Kessentini et al. [33] showed how well a flat plate collector with transparent plastic insulation and a cost-effective overheating protection system that operates in the 80–120 oC temperature range performed. A ventilation tube with a thermally activated door served as the protection device, preventing the system from entering a stagnant state. Simultaneously, the authors conducted trials on the collector prototype using numerical modelling. To verify the model and monitor the system's efficacy, tests were conducted both indoors and outdoors. The numerical model that was used was based on the resolution of several components, specifically the examination of heat transfer between distinct components and their subsequent integration using a modular object-oriented tool. This tool's primary benefit is that it allows you to parallelise the entire system and save computation time by substituting high-level CFD objects for each item or component. The two results showed good agreement. Additionally, the authors performed a parametric research to optimise the collector design by modifying the FPC component arrangement. Virtual prototyping was used to test 3125 possibilities, and the most promising ones were identified. The instantaneous efficiency of the collector was measured at 0.518, while the stagnation temperature of the transparent plastic-insulated cover reached 114.6 °C.

Research has shown that the distribution of flow has a considerable impact on the efficiency of solar collectors, with optimal performance occurring when the flow is uniform. Fan et al. [6] studied both the temperature and flow distribution of the collector fluid through experimental and analytical methods. Using a CFD model, they explored the heat transfer and fluid dynamics of a propylene glycol/water mixture within the collector. An experiment was conducted on a prototype of a suggested model to assess the flow distribution through the absorber based on temperature distribution data collected on the absorber tube's backside.

The study considered a number of parameters, including collector tilt angle, solar collector fluid characteristics, intake temperature, and flow rate. For high flow rates, the results of thermal analysis and CFD simulations agreed well, however for lower flow rates, there were significant discrepancies. It was discovered that the flow distribution was uniform at greater flow rates. The flow distribution became extremely irregular as the flow rate and mixture's glycol concentration dropped. Additionally, flow distribution deteriorated with increasing tilt angle and inlet temperature, raising the possibility of boiling in the collector's top section. However, it had little effect at greater flow rates. The buoyancy effect, which predominates at lower flow rates and becomes less significant at higher ones, may be the cause of this, according to the authors.

## 3. Development of collectors:

In order to properly capture solar heat, new methods and approaches must be used, as was previously said. The collector's overall performance and thermal efficiency are intended to be improved by these methods. To improve collector performance, numerous studies have been conducted by different scholars. Among the methods are modifications to absorber plate design, the use of diverse heat transfer fluids to absorb heat, and the building of the collector using a variety of materials.

### 3.1. Polymer usage

Polymer solar collector research was done by Martinopoulos et al. [4]. The authors created a polymer solar collector and used CFD and experimentation to study it. The lightweight nature and low manufacturing costs of polymer types provide them an advantage over metal types. Using this type of collector can result in a weight reduction of about 50% and a significant decrease in material costs. Large temperature changes and liquid pressure should not be a problem for the polymer material. For effective heat transfer to the working fluid, the polymer material through which the fluid flows must exhibit a high refractive index, comparable to or exceeding that of glass, along with low emissivity and resistance to UV degradation. To fulfill these requirements, the authors incorporated hydraulic channels made of transparent, UV-stabilized, honeycomb-structured LEXAN sheets. The sides were insulated using polyurethane, while a 1000/1 mixture of black Indian ink was chosen as the heat transfer fluid. The entire setup was enclosed in an aluminum casing.

An ISO 9806-1 test bed was used for the tests, and a computer was used to store the data from multiple sensors and measuring equipment. A completely organised grid of 1.2 million computational cells and 13 computational blocks was used for CFD modelling, with particular emphasis paid to areas near solid walls and inlet and outlet pipes. To take into consideration the honey comb structure and save time and computing power, the collector channel region was simulated as a porous medium zone. FLUENT was used for computation, and NUMECA/IGG was used for grid construction. Because of the collector's size, gravity was taken into account along with the buoyancy effect in the momentum calculation. The computed and experimental averaged efficiency figures were in excellent agreement. Using a computational model, it was discovered that several areas of the model were troublesome and caused the efficiency to drop. To improve the collector's overall efficiency, additional research might be conducted by altering the computer model to eliminate or reduce such areas. Missirlis et al. [40] investigated the heat transfer characteristics of polymer-based solar collectors, focusing on different manifold configurations for similar objectives. To maximize performance at the lowest possible cost, it is crucial to either select appropriate materials or optimize the design of the collector. In their study, the researchers employed CFD simulations to analyze how variations in manifold arrangements, specifically altering the positions of the inlet and outlet pipes, affected the system's performance.

The authors employed the previously created and verified CFD model. They used CFD to study the thermal behaviour and efficiency of the polymer collector by adjusting the inlet temperatures to cover the operating range. Optimising the flow field development and enhancing the collector's thermal behaviour were the study's objectives. According to the study, a small adjustment in the collector's design resulted in a noticeable gain in thermal energy while incurring no manufacturing costs. This demonstrates that CFD is an effective technique for design optimisation, which improves performance.

In order to optimise the collector's design, Mintsa Do Ango et al. [21] also focused on polymer-based solar collectors and performed numerical simulations to assess their performance. Traditional collectors, which are often made of copper or aluminum, tend to be costly. This challenge can be addressed by utilizing polymers in the construction of collectors. In their study, the authors investigated how various design factors, such as the thickness of the air gap and the length of the collector, along with operational parameters like mass flow rate, solar input, and inlet temperature, influenced the collector's efficiency. The collector used in their research consisted of a polycarbonate absorber, polycarbonate glazing, and glass wool insulation. It was tilted 45 degrees when in operation. The buoyancy effect was ignored in the numerical analysis, which was conducted under the assumptions of constant physical characteristics and grey and diffuse solid surfaces. The flow was viewed as laminar and the fluid was simulated as an incompressible Newtonian fluid. The ideal transparent gas and stationary system was thought to be air. The findings showed that the air gap had a greater impact on efficiency than the collector's length, with 10 mm being the ideal air gap for this specific setup type. An increase in mass flow rate lowered the fluid's output temperature while increasing efficiency. This kind of collector was not significantly impacted by solar radiation. The input temperature has a significant impact on efficiency; for optimal results, this parameter should be at least equivalent to the surrounding air temperature.

Peña and Aguilar [44] conducted a study on a polymer-based solar collector developed by the Mexican company Modulo Solar. They found that, for residential applications, the thermal performance of the polymer collector was comparable to that of traditional metal collectors. Due to their high elongation capacity, polymers are able to endure low environmental temperatures without requiring an external antifreeze valve.

### 3.2. Heat transfer fluid micro and mini channels

Mansour [9] performed a thermal analysis on a solar flat-plate collector utilizing minichannels to examine the pressure drop and heat transfer characteristics of the working fluid. The collector featured multiple minichannels embedded in the glass-covered absorber plate, with water serving as the heat transfer fluid. The primary benefit of the minichannel/microchannel heat exchanger that attracts researchers is its high potential for heat transmission, which combines the qualities of a big heat transfer coefficient, a small working fluid inventory, and a high surface area per unit volume. The goal of the authors' square minichannel-based solar collector design was to optimise thermal performance while requiring the least amount of electricity from the circulating pump. Two components made up the mathematical model created for the analysis. One is for thermal study of the collector as a whole, and the other is for numerical modelling to determine the working fluid's pressure drop and heat transfer coefficient. Laminar flow of Newtonian, incompressible fluid in steady state heat transfer was modelled numerically, ignoring viscous heat creation, dissipation, and any kind of internal or external force. The physical characteristics of both fluid and solid materials were regarded as constant, and flow was described as developing thermally and hydrodynamically. The set of equations was solved numerically using the finite-volume method with ANSYS FLUENT 12. To solve the pressure and velocity in the continuity and momentum equations, the SIMPLE algorithm was applied, utilizing a pressure-correction approach. The Gauss-Seidel method was employed iteratively. For the thermal analysis, the conventional fin analysis method was used, which treats the solid domain between the two fluid channels as a thin film. A software code was developed using EES to predict the collector's performance under various operating conditions. The results revealed that minichannel-based collectors offer a higher heat removal factor compared to traditional collectors. While higher flow rates enhance thermal performance, they also reduce the hydraulic efficiency of the collector. Deng et al. [35] explored the concept of a distinctive flat plate collector utilizing an array of micro-channel heat pipes. Numerous studies have demonstrated the effectiveness and temperature dispersion of heat pipe-based collectors. However, it has some drawbacks, including expensive cost, manufacturing technical challenges, high thermal resistance because of the smaller circular contact surface, fin efficiency's impact on heat transmission, scaling issues, etc. A microchannel heat pipe array-based collector was developed in order to overcome these limitations. Thin aluminium sheets with tiny grooves were used to create these channels in order to improve heat transfer. These arrays are preferable to the conventional kind because to their high compressive strength, low cost, minimal contact resistance, excellent heat transfer performance, and high dependability. To confirm the suggested micro channel heat pipe array's thermal performance, the authors first conducted a preliminary test. Under different testing conditions, the results showed a rapid change in temperature along the pipe, with a response time of under two minutes. When there was a 1 °C temperature difference between the evaporator and condenser, the system exhibited good isothermal performance alongside a quick thermal response.

The initial tests were successful, leading to the installation of the collector with these pipes for further evaluation. Performance testing was conducted in Beijing using the setup, following the Chinese standard GB/T4271-2007. The results showed that the maximum instantaneous efficiency reached 80%, which was 11.4% higher than the required Chinese standard. After comparing their findings with six groups of fifteen samples, the authors discovered that the highest instantaneous efficiency of their suggested collector design is more than 25% higher than the average level of the chosen samples. These results clearly highlight the promise of collectors utilizing microchannel heat pipe arrays. Wei et al. [7] developed an innovative design for flat plate collectors, which employed a single large wickless heat pipe instead of multiple smaller ones. When heat transfer occurs through forced or free convection in traditional type collectors, there are numerous issues. These include convective and radiative losses, corrosion-induced pipe deterioration, and freezing of water in colder climates. These days, heat pipes are frequently used in flat plate designs to improve performance. High stability and leak avoidance between the water cooling side and the solar heating side are the main benefits of the authors' design. The authors first tested the new collector design's thermal performance through an experiment. They then performed theoretical energy balance analyses for each component and developed a transient heat transfer model to determine the absorber plate, glass cover, and water temperatures as well as the collector efficiency. A water storage tank, a water pump, a valve, a flow meter, and a solar heat collector made comprised the setup for the experiment. The collector consisted of a glass cover, an absorber plate, an insulating layer, and an integrated heat pipe system featuring fifteen vertical pipes, two horizontal pipes connecting the vertical pipes at each end, and a pipe for returning the working fluid. Alcohol was chosen as the working fluid. Experimental results indicated that heating 200 kg of water by 25 °C achieved a maximum efficiency of 66%, which could be further improved by enhancing the thermal insulation.

**3.3. Nanofluids as a fluid for heat transfer**

There are several approaches to enhance the thermal performance of flat plate collectors. One such method is incorporating nanoparticles with high thermal conductivity, such as metals, metal oxides, or carbon, into the heat transfer fluid to improve the overall conductivity of the working fluid. Given that water has a relatively low thermal conductivity, finding an alternative fluid is essential for improving collector efficiency. The development of nanotechnology gave rise to a new class of fluids called nanofluids, which are composed of nanoparticles suspended in a base fluid. Zamzamian et al. looked into how Cu nanoparticles affected the flat-plate solar collector's efficiency [31]. $CuSO_4 \cdot 5H_2O$ was reduced in a single step using $NaH_2PO_2 \cdot H_2O$ in ethylene glycol as the solvent, resulting in the formation of Cu nanoparticles. Nanoparticles with sizes of 10 nm were utilized, with weight fractions of 0.2% and 0.3%. Ethylene glycol and nanofluid were the two types of working fluids used in the experimental apparatus. Variable flow rate experiments were conducted to examine the impact, and ASHRAE 93 requirements were taken into consideration when evaluating the collector's performance. The efficiency peaked at 1 l/min and declined as the volume flow rate fell, according to the results. Efficiency increased as the concentration of Cu particles increased, and the usage of nanoparticles also demonstrated a rise in the absorption parameter. The absorption parameter peaked at 1.5 l/min. The ideal operating conditions were determined to be 1.5 l/min with 0.3 weight percent Cu/EG nanofluid. Alim et al. [41] conducted additional research on nanofluids as heat transfer fluids, examining the flat plate collectors' rates of entropy formation, pressure drop, and energy destruction. The impact of nanoparticles Al2O3, CuO, SiO2, and TiO distributed in liquid was examined theoretically based on their capacity to improve heat transfer, generate entropy, and reduce pressure. The nanofluid's flow was regarded as axial, laminar, and stable. Parameters including solar radiation, total heat loss, and nanofluid properties were taken into consideration as constant across time in order to simplify the process. Energy creation and energy destruction were plotted as a function of nanoparticle volume concentration after the concentration and flow rate of the nanofluid were varied. The findings demonstrated that among the four metal oxides, CuO could boost heat transmission by 22.15% and decrease entropy formation by 4.34%. The pumping power of the CuO nanofluid increased slightly by 1.58%, which is within an acceptable range. Furthermore, the study found that the inclusion of nanoparticles enhanced heat transfer properties and improved the convection coefficient. As the nanoparticle concentration increased, the heat transfer performance was further enhanced, with no noticeable change in the friction factor compared to the base fluid. This demonstrates that nanofluids, especially those containing CuO, can effectively improve heat transfer characteristics without significantly increasing costs. To ascertain its impact on flat plate collector efficiency, Moghadam et al. [43] also conducted experiments using CuO-H2O nanofluid as a working fluid in the collection. The authors selected nanoparticles with an average diameter of 40 nm, 99.9% purity, and a fixed volume concentration of 0.4%. The mass flow rate was varied between 1 and 3 kg/min. The performance of the collector was evaluated using ASHRAE standards 86–93. Initially, efficiency increased as the mass flow rate rose but eventually started to decrease. At the optimal mass flow rate, efficiency was found to be 16.7% higher than that of a water-based collector. He et al. [20] also examined the use of nanofluid as a working fluid in solar flat plate collectors, specifically using Cu-H2O nanofluid. The thermal performance was assessed following the ASHRAE 86–93 standards, with a constant water mass flow rate of 140 l/h. Two particle sizes, 25 nm and 50 nm, were tested, and the experiments were conducted between 9:00 AM and 4:00 PM. The key variables tested were particle size and weight fraction. The results showed a maximum efficiency increase of 23.83% compared to a water-based collector. Efficiency was lower at 25 nm with a 0.2 weight percent concentration compared to 25 nm at 0.1 weight percent, indicating a decline in efficiency as the particle weight fraction increased. Larger particle sizes also resulted in decreased efficiency, likely due to the larger surface area of smaller particles, which are more susceptible to micro-convection effects in the water. Compared to water-based systems, there was a 12.24% increase in water temperature and a 24.52% rise in the heat absorbed. However, the frictional resistance for nanofluids was found to be somewhat high. Nasrin et al. [18] conducted a numerical study on the heat transfer performance of various nanofluids in solar collectors, selecting four nanofluids: Ag-H2O, Cu-H2O, CuO-H2O, and Al2O3-H2O. Their experiments were carried out using a flat plate insulated metal box solar collector with a dark-colored sinusoidal wavy absorber. The nanofluid's density was estimated using the Boussinesq approximation. The aim of the study was to analyze the behavior of the aforementioned nanofluids with respect to their solid volume fraction, considering factors such as temperature and velocity distribution, heat transfer coefficients, and mean velocity and temperatures. The numerical model was based on the Navier-Stokes and heat transfer equations. To solve the governing equations, Galerkin's finite element method was applied. The integrals of the resulting equations were solved using three-point Gaussian quadrature, while the Newton-Raphson method was employed to solve the non-linear residual equation. The results revealed that the 5% Ag nanoparticle exhibited the highest heat transfer rate. When the concentration of Cu increased from 0% to 5%, the collector efficiency rose from 65% to 85%. Hordy et al. [24] studied the stability of nanofluids under high temperatures and over prolonged periods. Additionally, they examined the optical properties of several nanofluids composed of a wide range of plasma-functionalized micro-walled carbon nanotube (MWCNT) particles. Base fluids such as water, ethylene glycol, propylene glycol, and Therminol VP-1 were used to create various nanofluids. The authors discovered that whereas water-based nanofluids exhibited slow agglomeration and Therminol VP-1-based nanofluids had a fast rate of degradation, glycol-based nanofluids were stable for an extended period of time, around eight months of testing. No agglomeration was seen at high temperatures, such as roughly 85 °C for water and 170 °C for glycol-based nanofluids. This demonstrates that nanofluids are stable at high temperatures and for extended periods of time. According to an optical investigation, these MWCNT-based nanofluids may absorb solar radiation across a broad spectrum, resulting in an absorption of around 100% of solar energy, even at low concentrations. Yousefi et al.'s experimental study on MWCNT-H2O [39] revealed that the collector's efficiency increased as the weight fraction increased from 0.2 to 0.4%. Additionally, experiments showed that using surfactants increases overall efficiency. Goudarzi et al. [23] explored how the pH levels of nanofluids affect the efficiency of solar collectors. The study used CuO-H2O and Al2O3-H2O nanofluids at concentrations of 0.1% and 0.2% by weight, respectively. The nanofluids were prepared in two stages: initially, the particles were mixed with distilled water, followed by homogenization through ultrasonic vibration. To enhance the stability of the mixture, a sulfonate surfactant was added. The experiment was conducted in a new cylindrical solar collector that consists of a black copper-based helical pipe as a receiver and a cylindrical glass tube cover with minimal reflectivity and maximum transmissivity. The efficiency of the collector increased as the difference between the nanofluid's pH value and its isoelectric point increased, according to the results. The efficiency of a CuO nanofluid with an isoelectric point of pH¼ 9.5 increased by almost 52% at pH¼ 3 compared to pH¼ 10.5. Similarly, the isoelectric point of Al2O3 is at pH¼ 7.4. This efficiency was 64.5% higher at pH¼ 10.5 than it was at pH¼ 9.2. Nanofluids were assessed by Faizal et al. [32] based on environmental and economic factors. One option to improve performance is to increase the collector's area, but doing so would make it larger, heavier, and bulkier. In order to create a smaller, lighter, and more compact collector that has the same output temperature as bulker ones, the authors of the study set out to use nanofluids as heat transfer fluids. Numerical models and previous studies were used to calculate size reduction, efficiency, energy savings, and cost reductions for CuO, SiO2, TiO2, and Al2O3 nanofluids. For 1000 units of solar collectors, the weight reductions observed were 10,239 kg for CuO, 8625 kg for SiO2, 8857 kg for TiO2, and 8618 kg for Al2O3. Nanofluids with low specific heat and high density demonstrated higher thermal efficiency, with CuO performing the best in this regard. The area reductions for CuO, SiO2, TiO2, and Al2O3 solar collectors were 25.6%, 21.6%, 22.1%, and 21.5%, respectively. The manufacturing process of these collectors could reduce CO2 emissions by 170 kg and save 220 MJ of embodied energy through the use of nanofluids as the working fluid. Compared to traditional detectors, which have a payback period of 2.49 years, these detectors showed a slightly shorter payback period of 2.4 years. Thus, incorporating nanofluids makes the collector more compact, cost-effective, and environmentally friendly. The use of nanofluids in direct absorption solar collectors (DASC) was also explored by Shende and Sundara [26]. Due to their excellent thermal conductivity, unique optical properties, strong mechanical strength, and large surface area, carbon nanostructures such as graphene and carbon nanotubes (CNTs) are ideal for creating nanofluids for DASC. In their study, the authors synthesized a nitrogen-doped hybrid structure of reduced graphene oxide (rGO) and multi-walled carbon nanotubes (N-(rGO-MWNTs)) as the nanoparticle. Ethylene glycol (EG) and deionized water (DI water) were used as base fluids for the nanofluids. The resulting nanofluids were highly stable, with no aggregation or settling due to the percolation network formed between the MWNTs and rGO through intercalation. Thermal conductivity as a function of temperature was measured through transmittance and absorption tests. The results showed a 15.1% increase in conductivity for EG and a 17.7% increase for DI water at 0.02% concentration. The fluids exhibited the ability to absorb light across a wide spectrum, from far ultraviolet to far infrared, due to their black color and larger surface area. Even small concentrations of these nanoparticles significantly enhanced the optical properties of the fluid, with absorption increasing as the concentration of nanoparticles rose. The study also found that the thermal conductivity of the fluids increased with both temperature and nanoparticle concentration.

### 3.4. Designs for absorber plates

The absorber is the key component of the collector responsible for capturing various wavelengths of solar radiation. To improve the collector's efficiency, it is necessary to apply a selective coating to the absorber. For applications requiring high thermal power, Jyothi et al. [14] developed an innovative tandem absorber made of nanostructured TiAlC/TiAlCN/TiAlSiCN/TiAlSiCO/TiAlSiO. In this design, TiAlSiO acts as an anti-reflective layer, TiAlSiCO functions as a semi-transparent layer, and the first three layers of the tandem absorber serve as the primary absorbing layers. As we move upward, the metallic characteristics of the material become less prominent. This tandem absorber, with an absorptance of 0.961 and thermal stability up to 650 °C, was deposited onto a W-coated stainless steel substrate. The authors used cross-sectional images obtained from a field-emission scanning electron microscope to determine the optimal thickness for the tandem layers, which were further verified through a transmission electron microscope. The absorber's performance was evaluated by heating it in air under vacuum at various temperatures. The results showed excellent thermal stability, maintaining performance up to 325 °C for 400 hours and up to 500 °C for 2 hours in air. In a vacuum, thermal stability was maintained up to 900 °C for two hours, and under cyclic heating, long-term stability was demonstrated at 650 °C for 100 hours. Del Col et al. conducted both computational and experimental studies on a prototype of a novel glazed flat plate collector utilizing a roll-bond aluminum absorber plate. [30] Roll bond absorber plates are specialized panels created using a distinctive bonding technique that involves sandwiching two aluminium sheets through a unique hot/cold rolling process. The plate's channel patterns are printed using a serigraphic method with a special ink that prevents welding in the desired areas. After the two sheets are welded together, high-pressure air is injected into the unbounded section to inflate it. The roll bond solar collector, featuring integrated liquid channels and equipped with inlet and outlet connections, is then fully assembled. By customizing and optimizing the flow patterns within the absorber, these collectors enhance and standardize the temperature distribution. A comparison was made between these collectors and traditional sheet-and-tube types, including one with copper black paint, another with an aluminium selective absorber, and additional configurations featuring black and semi-selective coatings. Four collectors in all, each with the same aperture area, were examined. In accordance with EN 12975-2, thermal efficiency measurements were conducted under both steady-state and quasi-dynamic settings. Collectors were handled as a sequence of overlapping components in the numerical model, and the steady state hypothesis-based computational procedure was split into two stages: initially, heat conduction between neighbouring control elements was ignored, and then thermal conduction was taken into account. Experimental results indicated that, for the same coating, the roll bond collector with a black coating outperformed the copper collector in terms of efficiency. The efficiency of traditional collectors increased as the number of tubes grew. For example, with twenty-eight tubes of the same diameter as the roll bond absorber, the efficiency was found to be equivalent. However, the production of these collectors faces technical limitations, making them neither practical nor cost-effective. A roll bond absorber with more channels is considered a better option. Additionally, numerical simulations show that thermal efficiency is highly sensitive to ambient temperature, with efficiency decreasing as the outside temperature rises. This factor must be taken into account when evaluating collectors. Air solar collectors are particularly suited for low-temperature applications like apartment heating and agricultural drying. These collectors typically use flat plate absorbers. A key design challenge for air collectors is the low heat transfer coefficient between the surface and the air. While fluid-wall surface area is less critical in water-based collectors, it is a crucial factor for air-based collectors. The low heat transfer coefficient results in reduced thermal efficiency. Enhancing efficiency can be achieved by increasing surface area and promoting turbulence within the channel. El-Sawi et al. [25] proposed an innovative chevron-patterned absorber design based on a continuous folding technique. This method involves passing a metal sheet through a series of grooved rollers and cross-folding rollers to create a fold. It is an environmentally friendly, efficient process that minimizes material wastage. The authors performed experiments to validate the performance of these new collectors and compared them to traditional flat plate models. The experiment considered variables like mass flow rate and inlet temperature. Results showed that the chevron-patterned absorber yielded a 20% increase in thermal efficiency and a 10°C temperature rise compared to the flat plate collector. These findings, supported by theoretical analysis, also indicated that the chevron design provided a 10% improvement over v-grooved absorbers and a 20% improvement over flat plate models. Due to its lower overall loss coefficient, the chevron-patterned absorber was found to be a more cost-effective and efficient alternative for air solar collectors.

**3.5. Making Use of PCM**

One of the main challenges with solar thermal systems is the storage of solar energy. These systems operate during the day, but in order to have access to hot water at night, storage tanks must be added, increasing both the size and cost of the system. Phase change material (PCM)-integrated solar collectors offer a promising solution, potentially eliminating the need for separate storage units. These collectors are advantageous due to their large storage capacity and isothermal behavior during the melting process. However, their low thermal conductivity remains a challenge. To overcome this limitation, significant research is being conducted to enhance the thermal conductivity of these PCMs. In a related study, Chen et al. [19] analyzed the energy storage performance of a solar collector that incorporates a porous structure filled with paraffin as the phase change medium. The paraffin absorbs solar energy throughout the day and stores it, while at night, the stored heat is transferred to water circulating through capillary tubes embedded in the paraffin. Since paraffin and aluminum frames have different thermal diffusivities, they were modeled separately in the study. The momentum conservation equation for paraffin was based on Darcy's law and its extension by Brinkman-Forchheimer, which was used for the numerical analysis of this design. Additionally, two temperature models were applied to simulate heat transfer in aluminum foam containing melting paraffin. The mathematical model ignored serpentine pipes because of their modest size and lack of impact. When melted, paraffin was represented as an isotropic Newtonian fluid. The bottom and side walls were regarded as adiabatic, and surface tension and curvature effects were disregarded. Physical characteristics were thought to be temperature independent for single phases, however they varied linearly with temperature for solid-liquid phases. The linked continuity momentum equation was solved using the SIMPLEC algorithm after the governing equation was discretised using FVM. The researchers initially used simulations to examine the performance of paraffin as a heat storage medium. They then explored a more advanced storage method involving an aluminium foam matrix soaked with paraffin. Studies showed that aluminium greatly enhanced the heat transfer rate and the melting of paraffin. When compared to pure paraffin, the temperature distribution in aluminium foam combined with paraffin was much more uniform. In a separate study, Serale et al. investigated the use of phase change materials (PCMs) in solar collectors [27]. They employed a previously developed numerical technique to assess the properties of a slurry PCM-based solar collector. In this study, the heat transfer fluid consisted of microencapsulated PCM (mPCM) dispersed in a solution of water and ethylene glycol, creating a mixture with consistent macroscopic fluid characteristics. This suspension of PCM improved the fluid's thermal properties. The results revealed an increase in instantaneous efficiency by up to 0.08 compared to traditional water-based collectors. However, the climate and the mPCM's melting point must be carefully optimized, as an incorrect setting could reduce the system's performance. Factors like location, flow rate, and mPCM concentration can be adjusted to further improve efficiency. In general, the heat gained from this system is consistently between 20 and 40 percent higher than traditional systems, depending on the conditions. The primary limitation of the system is that it cannot operate with mPCM concentrations exceeding 50%, as this would increase pumping energy consumption compared to conventional systems.

### 3.6. Reduction of heat loss

Heat losses from different components significantly affect the thermal efficiency of solar collectors. The upper portion of the collector, being fully exposed to the external environment, experiences substantial heat loss, primarily due to radiation and convection, with convection playing a more dominant role. Natural winds have a considerable effect, particularly on unglazed and single-glazed collectors, making it crucial to accurately determine the convective heat transfer coefficient influenced by wind. Although many wind tunnel experiments have been conducted to study this parameter, the actual effect in real-world conditions, where collectors are exposed to both sunlight and natural winds, may differ from what is observed in wind tunnel simulations. To assess the convective heat transfer coefficient from the top section of an unglazed solar collector, Kumar and Mullick [16] carried out experiments. The setup was placed on the roof of an IIT Delhi building, located in an area with minimal wind. For two years, data was gathered from February to May. Using this data, power regression and linear regression models were developed to correlate wind speed with the heat transfer coefficient using SigmaPlot software. The relationships found were compared to theoretical values and previous research on wind heat transfer coefficients at similar wind speeds. Considering the size of the collector, the findings can be applied to estimate the wind heat transfer coefficient in outdoor environments. In a separate study, Vestlund et al. [3] explored the possibility of enhancing the performance of flat plate collectors by replacing the air between the absorber and glass cover with an inert gas. The primary advantage of using gas to fill the enclosed space in solar collectors is the reduction in heat transfer rate, as well as a decrease in dust accumulation and condensation of humidity. However, the major challenge in utilizing various gases is the increased design complexity. These gases require sealed compartments, necessitating careful control of the gas filling volume and pressure. The pressure and volume of the gas directly influence the collector's performance and heat transfer properties. The authors investigated the effects of replacing air with different gases through computational heat transfer simulations. A mathematical model was developed using a one-dimensional heat transfer equation that incorporated radiation, convection, and conduction, with Matlab used for calculations. The collector's design and physical properties were based on a reference collector, a state-of-the-art flat-plate solar collector featuring anti-reflective glass and low heat loss. Heat transfer rates for both the top and bottom sections of the collector were incorporated, and sidewall insulation was excluded. The calculations also considered variations in the gap between the absorber plate and the glass cover to account for inconsistencies in the absorber design. The average results indicated that a thinner collector could be achieved with similar, or even better, performance than traditional collectors by using this gas filling method. While CO2 was an inexpensive option that produced a thinner collector, its performance did not meet the standards set by conventional designs.

Inert gases such as argon, krypton, and xenon were found to be much more effective and advantageous for solar collectors, despite their higher costs. The quantity required was small, allowing for the development of thinner collectors. After passing through the glass covers of flat plate collectors, solar energy is absorbed by the absorber plate. Some of the radiation is absorbed by the glass, while the rest is transmitted to the absorber plate. This absorption causes the temperature of the glass cover to rise, which can affect the heat transfer coefficients. Akhtar and Mullick [10] carried out a numerical study to explore how this absorption influences the heat transfer coefficients in single and double-glazed flat plate collectors. Their study aimed to assess how the absorbed radiation impacted the inner and outer surfaces of the glass, and consequently, the convective and radiative heat transfer coefficients. The numerical model incorporated heat transfer equations that accounted for radiation, convection between the glass covers and the surrounding space, and conduction within the glass itself. Variables such as the glass cover's thickness, incidence angle, hour angle, declination, location, and collector orientation, which affect solar energy absorption, were also considered. Empirical relationships were developed to calculate the inner and outer temperatures for both single and double-glazed collectors based on the study's findings. Comparisons were made between scenarios where absorption in the glass covers was considered and those where it was ignored. The results showed that the temperature of a single-glazed collector increased by 6 °C, while the temperatures of the first and second glass covers of double-glazed collectors increased by 14 °C and 11 °C, respectively. The heat transfer coefficients for the absorber plate varied by up to 49% between these two scenarios. In another study, Zhang et al. [30] conducted experiments to examine the effect of a heat shield on the thermal efficiency of a direct-flow coaxial evacuated-tube solar collector. The coaxial pipe was covered with a heat shield to minimize heat loss. The results showed that the solar collector's thermal efficiency increased to 54.07% at a maximum temperature of 123.9 °C with the heat shield, marking a 31.49% improvement compared to when no heat shield was used. The heat loss coefficient was also improved by 50.08%. Thus, heat shields proved to be an affordable and practical solution for enhancing the performance of evacuated solar collectors.

### 3.7. Utilising devices for enhancement

practical method for enhancing the thermal performance of solar collectors while keeping their size compact is to incorporate heat enhancement devices inside the pipes. These devices work by increasing the turbulence of the flow, which in turn improves heat transfer. Sandhu et al. [36] carried out a comparative analysis of various insert devices and their combined effect with the collector's inclination on efficiency. The study considered several types of insert devices, including three variations of twisted tape inserts with different pitch lengths: 1. short-pitch twisted tape, 2. medium-pitch twisted tape, and 3. long-pitch twisted tape. Additionally, the study looked at wire coil inserts, including simple coils, coils that are spaced away from the tube wall, conical coils, and mesh inserts. The experiments used water as the working fluid, with tests conducted across a wide range of Prandtl numbers (5–8) and Reynolds numbers (200–8000). The findings revealed that all insert devices increased the flow's Nusselt number, with the most significant increase observed in the transition and turbulent regions, while there was a slight decrease in the laminar zone. Among the wire coil family, the concentric wire insert delivered the best results, while among the twisted tapes, the short-pitch twisted tape showed the most promise. Concentric coils were especially effective in the turbulent region, increasing the Nusselt number by 460%. In contrast, mesh inserts performed best in the laminar region, enhancing the Nusselt number by 270%. However, mesh inserts led to higher friction and, consequently, increased pumping power consumption. Based on a 110% improvement in the laminar zone and a 460% improvement in the turbulent zone, the authors recommended concentric coils as the superior choice. The inclination tests showed that the collector's angle did not notably affect the Nusselt number.

Hobbi and Siddiqui [12] examined the effects of passive heat enhancement devices, such as conical ridges, coil-spring wires, and twisted strips, on a solar collector system. While they did not observe any significant changes in the heat flux to the collection fluid, they noted a substantial increase in the Grashof, Richardson, and Rayleigh numbers, suggesting that the heat transfer in the collector was primarily driven by mixed convection, with free convection playing a dominant role. The authors concluded that the use of inserts did not significantly improve heat transfer due to the damping effect caused by turbulence generated by buoyancy forces. In a similar vein, Martı´n et al. [08] conducted numerical simulations of a liquid solar collector using the TRNSYS software to assess the effects of wire inserts on its thermohydraulic performance. They focused on parameters such as local losses, friction coefficients, and the Nusselt number as functions of Reynolds number. The researchers developed a new collector model to better capture the internal heat transfer coefficient and friction factor. Their simulations followed the UNE-EN 12975-2 standards, and they used their own correlations alongside experimental data to evaluate heat transfer and pressure drop within the tubes. The study found that the efficiency of the modified collector increased by 4.5% compared to a standard collector. While pumping power increased across all water flow rates, there was no significant increase for a 44% propylene glycol mixture when the flow rate was below 80 kg/h. The increased friction caused by the inserts was identified as the primary reason for the rise in pumping power. Overall, the study concluded that wire inserts offer a viable way to enhance thermal performance and make solar collectors more compact, especially in warm climates or small-scale applications like residential water heating, where the pump size remains constant.

García et al. [15] carried out an experimental study to investigate the impact of wire-coil inserts on heat transfer in solar collectors. The experiment used two collectors with five different mass flow rates. The results showed that the addition of the wire-coil insert led to an efficiency increase of 14–31% and a rise in usable power by up to 8–12%, with no additional pressure losses. However, the efficiency improvement diminished as the mass flow rates increased. Many researchers have also explored the use of metal heat pipes as an effective means of enhancing the thermal performance of solar collectors. Despite their potential benefits, these collectors often face challenges such as being heavy, non-versatile, requiring complex assembly and installation, having low thermal efficiency, and experiencing high hydraulic resistance. To address these issues, Rassa-makin et al. [11] employed an extruded aluminium alloy heat pipe featuring longitudinal grooves and large fins in their design. The fins were placed on opposite sides of the heat pipes, acting as a heat sink surface. After a series of tests, the new design showed reduced thermal and hydraulic resistance, and it demonstrated high thermal efficiency. This innovation provided a lightweight, low-cost solution that significantly enhanced the thermal performance of the collector.

Tanaka [22] conducted a theoretical study to investigate the impact of using a bottom reflector on the performance of a solar absorber. The reflector and collector were positioned at an angle, with their fronts facing each other, enabling the collector to capture not only direct and diffused radiation but also the reflected light from the bottom reflector. A graphical method was employed to calculate the amount of radiation that was reflected and absorbed. The study revealed that the absorption of solar energy could be enhanced by adjusting the distance between the collector and the reflector. However, it was important to keep the gap between them smaller than the lengths of both the collector and the reflector. The optimal angle for the collector remained unchanged with varying gap lengths, although the reflector's angle adjusted slightly. When the gap was kept at an ideal length, the absorbed radiation decreased with increasing gap length, but the reduction was more pronounced at other angles.

Table 1 below provides a concise overview of all the development technologies.

**4. The extent of additional research**

| Sr.No | Research topic | Improvements and conversations |
|---|---|---|
| 1 | **Polymer as a medium for collection** | Benefits include being lighter and less expensive than metal collectors due to reduce production and material costs. High reflective index, low emissivity, UV durability, liquid pressure resistance, and compatibility with the HTF are desired qualities. Results: comparable to those of metal collectors. The efficiency is affected by the air gap but not by the collector's length. While efficiency rises with an increase in mass flow rate, output temperature falls. |
| 2 | **Mini and micro channels** | Benefits include a big heat transfer coefficient, a short working fluid inventory, and a high heat transfer potential that combines these qualities. High heat transfer efficiency, dependability, compressive strength, affordability, and little contact resistance are desired attributes. Research findings indicate that mini-channel collectors have a better heat removal factor. Thermal performance improves at greater flow rates at the price of hydraulic performance. When compared to conventional collectors, heat pipe channel arrays exhibit a very high efficiency and a low response time to temperature. |
| 3 | **Nanofluid as Heat Transfer Fluid (HTF)** | **Benefits:** Nanofluids as HTF can be used to create a lightweight, compact, environmentally friendly, and economical collector. More effectiveness than collectors that rely on water. Desired characteristics: the selected nanofluid should not agglomerate and should be stable over an extended period of time at a range of temperatures. High thermal conduction, a wide surface area, and favourable mechanical and optical characteristics are all necessary for nanoparticles used to create nanofluids. The results of the studies showed that efficiency increased as the number of nanoparticles increased. Efficiency declines as the nanofluid's volume flow rate drops. It is possible to achieve better convection coefficients and heat transfer phenomena without significantly raising the friction factor and pumping power. As particle size and weight fractions grow, efficiency falls. Heat gain overall rises. A long-lasting nanofluid based on glycol. Good thermal improvements are shown by CuO and Cu-based nanofluids. |

| | | |
|---|---|---|
| | | The uses of high density nanofluids can assist reduce the collector's area. |
| 4 | **Design innovation for absorber plates** | Benefits include an increase in the amount of heat absorbed from the sun.<br>Desired characteristics: must be able to efficiently absorb various wavelengths.<br>Research findings: a five-layered tandem absorber demonstrated excellent thermal stability over an extended period of time at high temperatures.<br><br>Although roll bond collectors are challenging to construct, they have shown promise in optimising and customising the absorber's internal flow patterns. Chevron pattern absorbers are more cost-effective and efficient than traditional collectors because of their distinctive design, which results in a low total loss coefficient. |
| 5 | **5. Making Use of Phase Change Materials (PCM)** | Benefits include reducing the bulk of water heating systems by doing away with the necessity for storage units. Offers a lot of room and behaves isothermally when melting.<br>High latent heat of transition, high density, low vapour pressure, minimal volume change, and high thermal conductivity in both liquid and solid phases, appropriate phase-transition temperature, chemical stability, and cost-effectiveness are the desired characteristics.<br>The results of the research showed that the temperature distribution of the paraffin-saturated aluminium foam matrix was superior to that of paraffin by itself.<br><br>mPCM exhibits improved thermal characteristics. Possess superior thermal efficiency compared to traditional PCM collectors. However, working with mPCM at concentrations higher than 50% is not feasible. |
| 6 | **Methods for reducing heat loss** | Benefits include improved efficiency as a result of less heat loss.<br>Desired characteristics: the method must be economical and reduce heat loss to the environment through radiation and convection.<br>Results of the research show that using alternative inert gases in place of air in the glass-absorber gap works well. With this method, thinner collectors can be produced at affordable prices.<br><br>A collector with two eyes is superior to one with just one. |

| | | |
|---|---|---|
| | | By placing a heat shield behind the tubes that convey fluid, heat loss is reduced and efficiency is increased. |
| 7 | **Using instruments for enhancement** | Benefits include reduced dimensions and improved thermal performance without alterations. Heat transmission in a fluid is increased by increased flow turbulence. Desired characteristics: should be able to raise flow turbulence without significantly increasing pumping power.<br><br>Results of the tests show that inserting devices increases the number of units in flow. Small-pitch twisted tape inserts showed promise. Although mesh inserts enhance pumping power, they are better for laminar flow. Concentric coils performed better in turbulence and laminar flow, although their pumping power did not much increase. The efficiency was increased via wire inserts. As the mass flow rate increases, the degree of augmentation brought about by the insert deteriorates. Heat pipes with fins and groves can be used to eliminate hydraulic and thermal resistance. The collector performs better overall when reflectors are used to guide photons onto it. |

The studies previously discussed all focus on the development and evaluation of solar flat plate collectors. Several numerical models have been created to accurately measure the performance of solar collectors, with these models typically based on key operating and design parameters. Research has highlighted the influence of various factors such as air flow rate, water inlet temperature, ambient temperature, inclination angle, and solar radiation. From these findings, a numerical model can be designed that treats each of these parameters as an independent variable, combining the effects of the most significant factors into a final equation to determine the collector's efficiency. This approach allows for the creation of an optimization study to identify the optimal values for design and operating parameters, improving the collector's performance. Some methods to enhance the flat plate collector include improving absorber design, selecting materials with high thermal conductivity and absorption capacity, increasing flow turbulence, using nanofluid to enhance thermal conductivity and surface area, integrating mini and micro channels for fluid flow, and incorporating thermal enhancements like inserts. A promising material in this context is graphene, which might be a suitable option. Graphene-based nanofluid, such as graphene/water, graphene oxide/water, or graphene Nano platelets combined with glycols, could serve as highly effective heat transfer fluids for solar collectors. The potential of using graphene/water nanofluid as a heat transfer medium remains largely unexplored. Studies have shown that graphene exhibits exceptionally high thermal conductivity, making it a stable and efficient fluid for this application. Additionally, using graphene in the form of Thermal Conductive Pyrolytic Graphite (TCPG) could further enhance the heat absorption and conduction capabilities of absorber plates.

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